

# Deep Convection in the Ocean

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## LONG-TERM GOALS

Our long-term objective is to understand how deep convection, induced by strong buoyancy forcing at the ocean surface, influences the ocean circulation through convective plumes and geostrophic eddies.

## OBJECTIVES

Issues specific to oceanic deep convection are the relatively strong role of rotation, such that convective Rossby numbers appropriate to the vertical motions may fall below unity; the highly intermittent nature of the forcing, with the strong impulses coming during the passage of atmospheric weather systems; the possible highly localized occurrence of deep convection; and the subsequent spatial redistribution and mixing of convected water by geostrophic mesoscale dynamics, which arise in part from instability of the localized convection regions. Our particular research projects are computational investigations intended to (1) quantify the extent to which penetrative mixing occurs at the base of a rotating convective layer, sharpening the pycnocline and entraining denser fluid from below; (2) determine how space/time intermittency in either the surface buoyancy flux or the pre-existing ocean stratification and circulation relate to the degree of localization of deep convection; and (3) explore the circumstances under which localized convected regions are persistent after the buoyancy forcing abates or undergo erosion through subsequent horizontal mixing and restratification of the gyre interior.

## APPROACH

High-resolution numerical simulations using the Boussinesq model developed in cooperation with our colleagues Drs. Keith Julien and Joseph Werne of NCAR are carried out on grids of  $256 \times 256 \times 129$  over domains of  $2\text{km} \times 2\text{km} \times 1\text{km}$  to investigate plume-scale dynamics. Conditionally sampled composite techniques are used to isolate the plume structures. The Boussinesq model is also used at coarser resolution over domains of  $50\text{km} \times 50\text{km} \times 2\text{km}$  to examine interactions between convection and simple examples of geostrophic circulation.

For more complex inhomogeneities in the initial conditions, larger horizontal domains and longer evolution times are required. Limited computational resolution then prevents resolution down to the plume scale, and a parameterization of the convective mixing is applied in these large domains (up to  $200\text{km} \times 200\text{km} \times 4\text{km}$ ). The use of an implicit gravity-wave Boussinesq model

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developed by Alistair Adcroft at MIT enables the use of longer timesteps, while representing the geostrophic adjustment process. We are studying the interaction between the vertical homogenization forced by the surface buoyancy loss and the preexisting eddy field, including the development of baroclinic instability, the horizontal homogenization of the mixed fluid by the eddy dynamics, and the possibility of persistence of isolated cores of mixed fluid, and comparing these phenomena with observations from the Labrador Sea ARI field program.

## **WORK COMPLETED**

(1) We completed a series of calculations of convection in the presence of a single mesoscale eddy where the eddies are associated with compensating anomalies in Temperature and Salinity, in addition to the density anomaly as studied in our previous work (Legg, McWilliams and Gao, 1998). As the flow evolves in response to surface buoyancy loss, considerable structure on a variety of scales is generated in the temperature and salinity fields. This variability often has no signal in the density field, and is therefore “density-compensated”. We have examined the budget for density compensated variability, and developed a parcel-exchange scaling argument to predict the magnitude of such variability. These results are described in an article “Temperature and Salinity variability in heterogeneous convection,” Legg and McWilliams, submitted to Journal of Physical Oceanography.

(2) We carried out a series of calculations over larger area domains (100km x 100km) containing ensembles of several dense and light core eddies, and comparison calculations without any eddies. In some calculations, convective buoyancy loss is applied to the upper surface; in others no forcing is applied and in some buoyancy loss is of only limited duration. These calculations have revealed a rich interaction between the convection and geostrophic eddy dynamics. We have focused on the modification of eddy statistics (the destruction and/or merger of eddies) and the energetics by the convective buoyancy loss. The results of this study are described in an article “Convective modifications of a geostrophic eddy field”, Legg and McWilliams, submitted to Journal of Physical Oceanography.

(3) Using solutions generated in the study of the interaction between convection and many geostrophic eddies, we examined the response of isobaric drifters to the plume and eddy scale motion, both at the surface and at depths of 1000m, employing 1600 drifters for good statistics. We are comparing these drifter statistics with those obtained by Breck Owens, Russ Davis and Karen Lavender using PALACE floats in the Labrador Sea. We have compared the statistics of the drifter measured fields (vertical velocity, temperature and salinity and horizontal velocities) to the Eulerian statistics. An article describing the eddy signatures of isobaric floats is currently in progress.

## **RESULTS**

(1) Temperature and salinity fine-structure.

We find that when both ambient stratification and a dense core eddy are associated with both salinity and temperature stratification, significant variability can be generated in the temperature and salinity fields without any corresponding density variability. This density-compensated variability can be generated through either vertical mixing or baroclinic eddy processes. We developed a simple parcel exchange theory to predict the magnitude of density-compensated variability. The mechanisms by which variability is created in vertical mixing regions and baroclinic eddy domi-

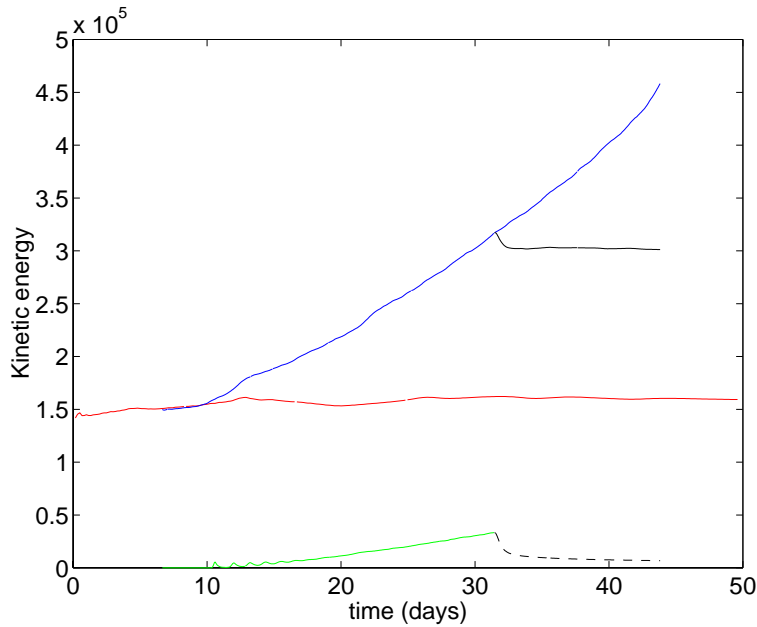


Figure 1: The evolution of the volume averaged total kinetic energy. Shown in red is the control case without any cooling for a field of geostrophic eddies. The rapid increase in kinetic energy induced by surface buoyancy loss applied to this field of eddies is shown in blue. When the buoyancy loss ceases (black) this high energetic state remains. In contrast, without any eddies in the initial conditions (green) the kinetic energy increase due to surface buoyancy loss is small, and rapidly dissipates when cooling ceases (black, dashed).

nated regions differs. In vertical mixing regions parcels of water from the surface are exchanged, via convection plumes, with parcels of the same density from the stable stratification at the base of the convective layer base. In the baroclinic eddy region the interleaving exchanges parcels along isopycnals between the center of the eddy near the surface, and outside the eddy below the surface. Comparison between the parcel exchange model predictions and simulated variability shows that the vertical mixing region is more efficient at dissipating this variability.

## (2) Convective modifications of geostrophic eddy field.

We find that, as for a single isolated dense core eddy, the application of surface buoyancy forcing can destabilize a baroclinic eddy, through erosion of the surface stratification, and cause it to break up via baroclinic instability. When cooling ceases the remaining eddy fragments rapidly coalesce such that a few isolated eddy cores can persist. The fluid around the eddy cores is however much more efficiently mixed (horizontally as well as vertically) than in the absence of convective forcing. This efficient mixing is a result of a very energetic barotropic horizontal velocity field which develops when convective forcing is applied (figure 1). We show that without any eddies in the initial conditions, no barotropic velocity field is generated. Convective mixing causes a direct input of kinetic energy on relatively small scales, those of convective plumes. However, at these scales, where flow is strongly 3-dimensional, the kinetic energy is rapidly dissipated. When eddies are present, convective forcing acts as a catalyst for the release of available potential energy from the eddies, via baroclinic instability. This kinetic energy input is at the larger scales dominated by geostrophic dynamics, and hence cascades to larger scales, instead of being dissipated.

(3) Behavior of floats in convecting flows.

Our investigations of isobaric floats in the presence of convection localized by mesoscale eddies reveal a tendency for floats to congregate in the convergent regions associated with downwelling fronts. These fronts are associated with cooler than average fluid - hence the ensemble mean temperature measured by the floats diverges from the Eulerian mean, an important consideration when interpreting observations made by such isobaric floats. As a result the net heat flux deduced from the floats is about half that found from the Eulerian measurements. In flows with considerable eddy structure, the dispersion of floats can also reveal the process of lateral exchange and restratification.

## **IMPACTS**

Our research on convective dynamics should improve understanding of both the observed features of convection, and the net effects of these small-scale features on water mass transformation. This understanding provides a firmer basis for predictions of sub-polar circulations and tracer distributions and the global thermohaline circulation.

## **TRANSITIONS**

These results are being shared with members of the ONR Labrador Deep Convection ARI. Our results are included in the article documenting the Labrador Sea convection experiment (Labsea group, 1998). Our recent results are being used to interpret the results of mooring measurements (Lilly et al, 1998), especially the appearance of strong barotropic eddy velocities during convection periods, and CTD measurements (Pickart et al, 1998) especially the structure in temperature and salinity fields. Float studies are being compared with the PALACE floats of Davis, Lavender and Owens, funded by ONR.

## **RELATED PROJECTS**

This work is carried out in collaboration with the “Mesoscale variability in the Labrador Sea” project, Legg PI, WHOI.

### **ONR Deep Convection ARI**

Our simulations of convection localized by one or more mesoscale eddies provide scenarios for comparison with observations, both of the small scale velocity and temperature fields, and remote sensing signatures of the chimney scale circulation and baroclinic instability eddies. These simulations encourage the evaluation of the pre-convection eddy field for comparison with the later localized convection regions. Our plume structure analysis provides detailed statistics on plume property distributions, for comparison with data from observations.

### **ONR Marine Boundary Layer ARI**

Our studies of deep convection driven by surface cooling overlap with studies of the oceanic and atmospheric planetary boundary layers. We are engaged in a long-standing partnership with Chin-Hoh Moeng and Peter Sullivan of NCAR, making Large Eddy Simulations of boundary-layer turbulence and comparisons with the field observations made in this program.

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